Crack Opening Area of Pressurized Pipe for Leak-before-Break Evaluation*

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The prediction method for analyzing the crack opening area of a pipe is essential for leak-before-break evaluation. Several theoretical approaches are proposed for predicting crack opening areas. One approach is the Tada and Paris formula, developed based on the linear elastic fracture mechanics. Another is the engineering approach developed by German and Kumar. Round-robin analyses for crack opening areas are performed using these two methods. The pipe analyzed is a 6-inch-diameter Type 304 stainless steel pipe with a circumferential through-wall crack. The applied load is bending moment. The crack opening areas calculated by Tada and Paris method coincided among the four participants. However, the areas using German and Kumar method were quite different. It is concluded that in the present situation, Tada and Paris method is suitable for a leak-before-break standard to predict the crack opening area. In addition, material properties used in the calculation of the standard are discussed compared with the results of the pipe bending experiment.

Key Words: Crack Opening Displacement, Jet, Plastic Instability, Leak Before Break, Leak Rate, Crack Opening Area, Stainless Steel Pipe

1. Introduction

Fracture experiments and analyses for pressurized pipes have been actively performed for the pre-

vailing leak-before-break (LBB) concept^{(1)~(3)}. In the last decade, more than ten international seminars on LBB have been held^{(4),(5)}. The verification of LBB is discussed together with the establishment of piping fracture mechanics. Several countries are making regulations pertinent to LBB acceptance and are attempting to apply the LBB concept to power generating plants^{(6),(7)}.

When the LBB concept is applied to power generating plants, it requires not only piping fracture analyses but also analyses of leakage from cracks in pipes and jet force impingement caused by a pressurized medium. The leak flow rate and jet force are directly related to crack opening areas. The prediction of crack opening areas is therefore essential for LBB evaluation.

Several approaches to predict crack opening areas are proposed, e.g., approaches based on the Dugdale model which takes into account the plastic zone at the crack tip⁽⁸⁾, and others based on linear fracture mechanics^{(9)~(11)} and on the plastic deformation theory⁽¹²⁾.

When designers calculate the leak rate and jet force, the solutions obtained should be a unique value

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under the same boundary conditions. Such calculation methods for leak rate and jet force are applicable to regulations and design standards.

This paper describes the results of round-robin analyses of crack opening areas. The approaches used to predict crack opening areas are the Tada and Paris method reported by the USNRC (US Nuclear Reactor Commission) and the German and Kumar method reported by the EPRI (Electric Power Research Institute). The pipe of interest here is of the Type 304 stainless steel with a circumferential through-wall crack. From the results of round-robin analyses and a pipe bending test, a suitable method for predicting the crack opening area for LBB standards is indicated, and the crack opening area for leakage and jet force assessment is discussed.

2. Methods for Predicting Crack Opening Areas

The formula of the Tada and Paris method is based on linear fracture mechanics⁽¹¹⁾. The crack opening area, S_b , for a circumferential through-wall cracked pipe subjected to bending moment is given by

$$S_b = \frac{\sigma_b}{E} (\pi R^2) I_b(\theta), \quad (1)$$

where σ_b is the nominal bending stress, E is Young's modulus, R is the mean radius of the pipe, and $I_b(\theta)$ is the nondimensional function as follows:

$$I_b(\theta) = 2\theta^2 \left\{ 1 + \left(\frac{\theta}{\pi} \right)^{3/2} \left[8.2 - 12.7 \left(\frac{\theta}{\pi} \right) + 19.3 \left(\frac{\theta}{\pi} \right)^2 \right] + \left(\frac{\theta}{\pi} \right)^3 \left[20.4 - 68 \left(\frac{\theta}{\pi} \right) + 165.2 \left(\frac{\theta}{\pi} \right)^2 - 187.2 \left(\frac{\theta}{\pi} \right)^3 + 146.7 \left(\frac{\theta}{\pi} \right)^4 \right] \right\} \quad (0 < \theta < 100^\circ), \quad (2)$$

where θ is the half-crack angle. In considering the effect of the plastic zone at the crack tip, the following equation of θ_{ef} is used instead of θ :

$$\theta_{ef} = \theta + \frac{K^2}{2\pi R \sigma_y^2}, \quad (3)$$

where σ_y is the reference yield stress and K is the stress intensity factor of the bending moment. Equation (1) is used when the ratio of the mean radius R and the wall thickness t of the pipe, R/t , is approximately 10.

The German and Kumar method gives the result of crack opening displacement δ for pipes⁽¹²⁾. The crack opening area is obtained from δ . The formula of δ is based on the fully plastic theory using the stress σ and strain ε of the Ramberg-Osgood representation. The relation of σ and ε of the Ramberg-Osgood representation is given by

$$\frac{\varepsilon}{\varepsilon_y} = \frac{\sigma}{\sigma_y} + \alpha \left(\frac{\sigma}{\sigma_y} \right)^n \quad (4)$$

where σ_y is the reference yield stress, ε_y is the refer-

ence plastic strain, α is the material coefficient and n is the strain hardening coefficient.

When a pipe with a through-wall crack receives bending moment M , the crack opening displacement δ is expressed by

$$\delta = f_2 \left(a_e, \frac{R}{t} \right) \frac{M}{E} + \alpha \varepsilon_y a h_2 \left(\frac{\theta}{\pi}, n, \frac{R}{t} \right) \left(\frac{M}{M_0} \right)^n, \quad (5)$$

where a is the half-crack length given as $a = \theta R$, a_e is the effective crack length containing the correction of small-scale yielding, t is the pipe-wall thickness, f_2 and h_2 are functions obtained from the elastic and fully plastic solutions shown in the table of Ref. (12). M_0 is the plastic collapse moment for the cracked pipe and is given by

$$M_0 = 4 \sigma_0 R^2 t \left(\cos \frac{\theta}{2} - \frac{1}{2} \sin \theta \right), \quad (6)$$

where σ_0 is the flow stress.

When the δ is obtained from Eq. (5), the crack opening area S is expressed by:

$$S = \frac{\pi a \delta}{2}, \quad (7)$$

where the crack is assumed to be ellipsoidal in shape.

3. Round-Robin Analyses

3.1 Analyses conditions

The pipe for the round-robin analyses is a 6-inch diameter (outer diameter of 165 mm) Type 304 stainless steel pipe with a circumferential through-wall crack of $2\theta = 90^\circ$. The applied load is pure bending moment without internal pressure. The analyses conditions are shown in Table 1. The four organizations which participated in the round-robin analyses are listed in Table 2.

The pipe fracture test was performed by the Japan Atomic Energy Research Institute (JAERI) as the "Pipe Reliability Verification Test" project⁽¹³⁾. The specimens used were 6-inch diameter Type 304 stainless steel pipes containing circumferential through-wall cracks. The experiment was performed at ambient temperature. The pipe bending test is illustrated in Fig. 1. As the crack opening displacement δ was obtained from the experiment, the δ was compared with the results of the round-robin ana-

Table 1 Conditions of round-robin analyses

Material		Type 304 stainless steel
Pipe	Diameter	165mm (6-inch)
	Thickness	10.8mm
Crack	Geometry	Circumferential through-wall crack
	Angle	$2\theta = 90^\circ$
Load		Pure bending without internal pressure

lyses.

There are three cases of the round-robin analyses, as shown in Table 3. Case I is the Tada and Paris method. The material constants of E and σ_y used in this analysis were the values obtained from the experiment. This method directly gives the crack opening area S shown in Eq.(1). The calculated S is converted to crack opening displacement δ using Eq.(7) for comparison with the δ of the experimental data.

Case II is the German and Kumar method. The objective is to check the participants' computer program. The material constants E and σ_y for case II, as shown in Table 3, are the same values as in case I. The coefficients α and n for the Ramberg-Osgood representation are arbitrary integers.

Case III, the main analysis of this paper, also uses the German and Kumar method. The material constants for the calculation were determined from the stress(σ)-strain(ϵ) curves obtained from the experiment. The nominal σ - ϵ curve for Type 304 stainless steel at ambient temperature was provided for the participants. The σ - ϵ curve is shown in Fig. 2. The

curves of Figs. 2 (a) and (b) are the same, but the curve in Fig. 2(a) is exaggerated at the small-strain range. The material constants were determined by the participants themselves and the crack opening areas were calculated using the material constants.

3.2 Analyses results

The relationship between crack opening displacement δ and nominal bending stress σ_b is shown in Fig. 3, which is case I, using the Tada and Paris method. The δ in Fig. 3, as explained earlier, is converted from the area S using Eq.(7). It can be observed that the calculated δ coincides among the four participants. Also included for comparison in Fig. 3 is the crack opening displacement obtained from the experiment.

The analysis result of case II is shown in Fig. 4. The δ - σ_b curves are consistent among the four participants. The computer program of the German and Kumar method indicates that there is no difference among the participants.

For case III with the German and Kumar method, the material constants determined by each participant using the σ - ϵ curves of Fig. 2 are shown in Table 4. Participants A and B have determined the material constants from Figs. 2 (a) and (b), respectively. Participant C has obtained the δ for the cases where

Table 2 Participants of round-robin analyses

Hitachi Ltd.
Ishikawajima Harima Heavy Industries Co., Ltd. (IHI)
Mitsubishi Atomic Power Industries, Inc. (MAPI)
Japan Atomic Energy Research Institute (JAERI)

Table 3 Cases of round-robin analyses

Test case	Scheme	Material constants (Room temperature)
Case I	Tada & Paris (NUREG CR3464)	fixed $E=194,000$ MPa $\sigma_y=243$ MPa
Case II	German & Kumar (EPRI NP3607)	fixed $E=194,000$ MPa $\sigma_y=243$ MPa $\alpha=1.0$ $n=5.0$
Case III	German & Kumar (EPRI NP3607)	determine from σ - ϵ curves of Figs.2 (a) and (b)

σ_y =yield stress, E =Young's Modulus

Fig. 1 Four-point bending test for pipes

(a) Small strain range

(b) Large strain range

Fig. 2 Stress-strain curves for Type 304 stainless steel

$\alpha=1.0$ and 2.0, taking into account the small and large strain range of Figs. 2 (a) and (b). Participant D has only used the curve of Fig. 2 (b) and obtained the material constants from a true σ - ϵ curve and a nominal σ - ϵ curve. The material constants were quite different among the four participants. Needless to say, the material constants shown in Table 4 can precisely represent the σ - ϵ curves of Fig. 2. The analysis result of case III is shown in Fig. 5. It can be seen that the δ - σ_b curves determined by the four participants are quite scattered.

3.3 Crack opening area for evaluation

The representation of the crack opening area proposed by the Tada and Paris method consists of a simple formula. The material constants in the formula are σ_y and E . Therefore, when designers calculate

crack opening areas for cracked pipes, they will obtain the same values.

On the other hand, the crack opening areas calculated by the German and Kumar method using the σ - ϵ curve are supposed to be different among the designers. The reasons for the different results are considered as follows.

First, the determination of the material constants of α and n in the Ramberg-Osgood representation is not clear from the experimental σ - ϵ curves. Secondly, there is discrepancy in the calculation method of the f_2 and h_2 . The f_2 and h_2 in the table of Ref. (12) were obtained from the finite-element calculation for each case of crack length, pipe diameter and wall thickness. The f_2 and h_2 are given when the R/t and n are integers, such as $R/t=5, 10, 20$ and $n=1, 2, 3, 5, 7$. Herein, when R/t and n are decimals, finite-element calculation is performed again to obtain the f_2 and h_2 functions. As the calculation takes much time, simple procedures such as interpolation and extrapolation are used to obtain the f_2 and h_2 . However, the proce-

Fig. 3 Crack opening displacement of case I

Fig. 4 Crack opening displacement of case II

Fig. 5 Crack opening displacement of case III

Table 4 Material constants determined by each participant

Organization	σ - ϵ curve used	α	n	σ_o MPa	E GPa	ϵ_y	Remarks
A	A-1 Fig.2 (a)	2.270	10.218	243	194	0.00124	Engineering σ - ϵ
	A-2 Fig.2 (b)	1.173	7.874	243	194	0.00124	"
B	B-1 Fig.2 (a)	0.0036	9.046	110	219.5	0.0005	"
	B-2 Fig.2 (b)	0.7193	5.995	176	194	0.0009	"
C	C-1 Figs.2	1.0	7.0	243	194	0.00124	"
	C-2 (a) & (b)	2.0	7.0	243	194	0.00124	"
D	D-1 Fig.2 (b)	6.10	4.33	243	194	0.00125	True σ - ϵ curve
	D-2 Fig.2 (b)	5.16	5.42	243	194	0.00125	Engineering σ - ϵ

σ_y =yield stress, E =Young's Modulus, ϵ_y =yield strain

dures were different among the participants. For example, the f_2 and h_2 were determined by proportional allotment, by functions of R/t and n , and by the relation of the functions between R/t and n and reciprocals of f_2 and h_2 . The f_2 and h_2 were different when the R/t and n were decimals.

When the crack opening area is applied for LBB standards, α , n , f_2 and h_2 should be unified. More precise research is needed to determine these parameters for Type 304 stainless steel. Consequently, the Tada and Paris method is suitable for predicting the crack opening area for the leak rate and jet force assessment in the present situation.

4. Crack Opening Area for LBB Standards

From the results of the round-robin analyses, the Tada and Paris method is employed here as the formula for determining the crack opening area.

The calculated crack opening displacement was larger than in the experimental data, as shown in Fig. 3, when the 0.2% yield stress obtained from the experiments is substituted for the reference yield stress. Therefore, a suitable reference yield stress is discussed hereafter, in comparison with the experimental data of the pipes.

The experimental data were supplied from the "Pipe Reliability Verification Test" project performed by JAERI. The test specimens were 6-inch diameter Schedule 80 Type 304 stainless steel pipes with circumferential through-wall cracks of $2\theta = 60^\circ$, 90° , 120° and 150° . The mechanical properties of the pipe specimens are shown in Table 5. A four-point bending moment, as shown in Fig. 1, was applied to the pipes without internal pressure at ambient temperature. The clip gages were mounted at the center of the crack length to measure the crack opening displacement δ . The crack opening areas S were obtained from the δ using Eq. (7). The δ is the crack opening displacement of the initial crack angle and does not include the crack opening displacement after the growth of a ductile crack from the initial crack.

The crack opening area S calculated from the Tada and Paris method is shown in Fig. 6, compared with the S obtained from the experimental data. In the calculation, three stress values σ_y and σ_u from Table 5, and σ_o , where $\sigma_o = (\sigma_y + \sigma_u)/2$, were chosen as

Table 5 Mechanical properties of pipe material

0.2% Yield stress, σ_y MPa	Ultimate tensile stress, σ_u MPa	Elongation %	Reduction of area %
243	619	68.7	52.1

the reference yield stress for the Tada and Paris formula.

The crack angle of the pipe in Fig. 6 is $2\theta = 90^\circ$. The crack opening area S obtained from the reference yield stress of σ_y is the largest, and the S from σ_u is the smallest. A nearly identical value to that in the experimental data was obtained from σ_o . The tendency of this S was similar to the areas of the angle crack of $2\theta = 60^\circ$, 120° and 150° .

If the material constants are unified, a unique value of the crack opening area is given, and it is easy to compare it with other steels and at different temperatures. In addition, it can facilitate the reflection to the design standards for assessments of the leak flow rate and jet force impingement.

It is conceivable that the yield stress and ultimate tensile strength defined in Notification No.501⁽¹⁴⁾ published by the Ministry of International Trade and Industry (MITI) are suitable for use as the material constants. The yield stress and the ultimate tensile strength in the Notification are 206 MPa and 519 MPa for Type 304 stainless steel at ambient temperature, which are equal to ASME Code Sec. III. The flow stress expressed in the Notification is symbolized to be σ_s . The flow stress is taken as the average of the yield stress and the ultimate tensile strength, and $\sigma_s = 363$ MPa for Type 304 stainless steel at ambient temperature.

The crack opening areas S for crack angle of $2\theta = 60^\circ$ and 90° obtained from σ_s are shown in Fig. 7. Figure 8 shows the crack opening areas for crack angles of $2\theta = 120^\circ$ and 150° . The crack opening areas calculated from σ_s are slightly smaller than the experimental data except for the area of $2\theta = 120^\circ$.

The ratio of crack opening areas obtained from the calculated S_{cal} and experimental S_{exp} is shown in Fig. 9 for various crack angles. When S_{cal} is less than

Fig. 6 Crack opening area of pipe substituting the reference yield stress of σ_y , σ_u and σ_o obtained from the experiment

S_{exp} , the estimated leak rate becomes smaller than the actual leak rate, and it gives a conservative estimate from the viewpoint of LBB.

It is considered that the leakage from a cracked pipe occurs under normal operating conditions. Piping systems are generally constructed based on the design stress. The design stresses of Type 304 stainless steel are 137 MPa at ambient temperature and 115 MPa at 300°C. The internal pressure of Schedule 80 pipe is used as less than 80 atm (7.84 MPa). The applied stress, taking into account the internal pressure, dead weight and so on, is about 60 MPa for pipes under normal operation. That is, the applied load at leakage should be estimated to be a low stress of less than 60 MPa. When we look at the ratio S_{exp}/S_{cal} in Fig. 9, it becomes $S_{exp} \geq S_{cal}$ at the low-stress level. The crack opening area calculated from the flow stress in Notification No.501 is close to the experimental value and gives a conservative estimate from the LBB viewpoint.

Fig. 7 Crack opening areas obtained from the material constants in Notification No.501 ($2\theta = 60^\circ$ and 90°)

Fig. 8 Crack opening areas obtained from the material constants in Notification No.501 ($2\theta = 120^\circ$ and 150°)

On the contrary, when the jet force caused by a pressurized medium is estimated, the calculated jet force must be larger than the actual jet force for a conservative estimate. The crack opening area for the jet force should be $S_{exp} \leq S_{cal}$. Also, excess load is generally applied to the pipe when the jet force is needed to assess the pipe. The applied stress is considered to have a wide range, up to pipe failure stress. When the applied load and crack angle are extremely large, pipe failure assessment is needed rather than jet force impingement. The S_{exp}/S_{cal} for the pipe in Fig. 9 with the crack of $2\theta = 150^\circ$ increases rapidly at the stress level of more than 140 MPa. At 140 MPa, the net-section stress at the crack ligament approaches the flow stress, and the condition of the pipe with the crack of $2\theta = 150^\circ$ is near failure.

From Fig. 9, the ratio S_{exp}/S_{cal} is within 1.5, except for the $2\theta = 150^\circ$ and $\sigma_b = 140$ MPa pipe. It is asserted that the crack opening area for jet force assessment is 1.5 times the value calculated from the Tada and Paris method using the flow stress σ_s . The crack opening area gives a conservative estimation for jet force impingement.

5. Conclusions

When a pressurized medium leaks or jets from a pipe crack, plastic strain may occur at the crack tip and the pipe may deform with plasticity. Under such stress conditions, the fully plastic theory is applicable to the pipe. The German and Kumar method based on the fully plastic theory shows the actual behavior of the cracked pipe, in contrast to the Tada and Paris method based on linear fracture mechanics. However, from the round-robin analyses and the comparison of the experiment, the following are concluded.

- (1) The Tada and Paris method is more suitable for LBB standards than the German and Kumar method to predict a crack opening area in the present situation.
- (2) When a crack opening area is needed for leak

Fig. 9 The ratio of crack opening areas obtained from the calculations and experiments

rate assessment, the material constants used are the flow stress based on the yield stress and the ultimate tensile strength defined by MITI Notification No.501.

(3) When a crack opening area is needed for the assessment of jet force impingement, the crack opening area is 1.5 times the value derived from the Tada and Paris method.

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